

Gravitational Fragmentation in Galaxy Mergers: A Stability Criteria.

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ABSTRACT

We study the gravitational stability of gaseous streams in the complex environment of a galaxy merger, because mergers are known to be places of ongoing massive cluster formation and bursts of star formation. We find an analytic stability parameter for case of gaseous streams orbiting around the merger remnant. We test our stability criteria using hydrodynamical simulations of galaxy mergers, obtaining satisfactory results. We find that our criteria successfully predicts the streams that will be gravitationally unstable to fragment into clumps.

Subject headings: galaxies: instabilities - galaxies: mergers - galaxies: star clusters

1. Introduction

Galaxy mergers are believed to be not just common events in the universe, but also fundamental pieces in the evolution of galaxies since they trigger bursts of star formation (Larson & Tinsley 1978; Sanders & Mirabel 1996) and they are a key ingredient in the formation Elliptical Galaxies and Bulges (Toomre & Toomre 1972; Mihos & Hernquist 1996; Kazantzidis et al. 2005; Di Matteo et al. 2007). More recently, it was also found that many interacting and merging galaxies are places of current massive cluster formation (Schweizer 1998; Mengel et al. 2008).

Standard numerical simulations of galaxy mergers that include gas (Barnes & Hernquist 1996; Kazantzidis et al. 2005; Cox et al. 2006; Di Matteo et al. 2007), have been able to reproduce the observed starbursts occurred during the merging process on nuclear gaseous disks. However, they intentionally avoid fragmentation through high minimum temperatures and large gravitational softening lengths, therefore, they failed to reproduce formation of massive star clusters. Only recently, simulations have the resolution required to study the gas fragmentation on at least large scales (Bournaud et al. 2008; Saitoh et al. 2009; Teyssier et al. 2010; Matsui et al 2012). In those simulations, massive star clusters are indeed formed

by gas fragmentation into collapsing clumps and therefore is relevant to have a criteria for gravitational instabilities in such complex environment.

The study of gravitational stability of fluids started with the work of Jeans (1902) for an uniform, infinite and isothermal gas. Later extended by Bonnor (1956) and Ebert (1955) for a finite and spherically symmetric fluid, a rotationally supported one (Toomre 1964; Goldreich & Lynden Bell 1965), a magnetized fluid (Chandrasekhar & Fermi 1953), among others. In this letter, we study the stability of the gaseous streams in the complex environment of a galaxy merger, by means of Smoothed Particle Hydrodynamics (SPH) numerical simulations.

This work is organized as follows. We start with a discussion of the physical processes relevant in stabilizing gaseous streams in galaxy mergers, with analytical estimates for a stability criteria in §2. Section 3 continues discussing the setup of the galaxy mergers simulations and the numerical requirements needed to resolve gravitational instabilities in galaxy mergers. In §4, we test the stability criteria by performing hydrodynamical simulations of galaxy mergers with the resolution discussed in §3. Finally in §5, we summarize the results of this work.

2. Basic Physical Ingredients: Pressure and Motion

High resolution simulations of galaxy mergers generally found galactic streams, such as tails and bridges at large scales and more complex ones on the inner kpc scales, in which collapsing clumps are ubiquitous features formed by gravitational instabilities. However, no gravitational instability criteria for the complex and irregular case of gaseous streams in a galaxy merger has been found.

The most basic physical processes that could overcome gravity in absence of magnetic and other fields, are gas pressure and motion. Since gas pressure is isotropic, does not depend on the geometry of the fluid, only on its local density and temperature, therefore its stabilizing role on small scales is the same that in a fluid with a regular geometry (i.e with a given symmetry). On the other hand, the motion of streams is much more complex and not constrained to a single plane, but on its central regions (inner kpcs, where the bulk of the star and cluster formation happens) is characterized by streams orbiting around the center of mass of the newly formed system.

A simple and useful approach, is to model individual streams as a piece of a rotating annulus. In such a case, from vector calculus is known that the rotational component of its motion is well described by an angular frequency, which is defined relative to an origin O of

the coordinate system in which we describe the motion:

$$\vec{\Omega}_o = \frac{\vec{r} \times \vec{v}}{\vec{r} \cdot \vec{r}} = \frac{\vec{r} \times \vec{v}}{r^2} = \hat{r} \times \frac{\vec{v}}{r} , \quad (1)$$

where $\vec{r} = r \hat{r}$ and \vec{v} are, respectively, the position and velocity vectors.

Under this approximation, the stability of individual streams is a very similar problem to the stability of annuli in a rotating sheet, with the difference that the streams in the merger case do not belong to the same plane ($\vec{\Omega}_o$ of individual streams can have a different magnitude and direction). In such a case, from dimensional analysis it is straightforward to conclude that results from standard gravitational instability analysis in a rotating sheet (Toomre 1964; Goldreich & Lynden Bell 1965; Binney & Tremaine 2008) should still be valid for a given stream: there is a range of unstable length scales limited on small scales by thermal pressure (at the Jeans length $\lambda_{\text{Jeans}} = C_s^2 / G \Sigma_{\text{gas}}$) and on large scales by rotation (at the critical length set by rotation, which for this case can be defined as $\lambda_{\text{rot}} \equiv \pi^2 G \Sigma_{\text{gas}} / |\vec{\Omega}_o|^2$). Only a combination of pressure and rotation can stabilize the stream, this happens when the range of unstable wavelengths shrinks to zero (i.e. the two scales are comparable) and this occurs for $\lambda_{\text{Jeans}} \geq (q/\pi)^2 \lambda_{\text{rot}}$ (Escala & Larson 2008). Therefore a stream will be stable if:

$$|\vec{Q}_o| \equiv \frac{C_s |\vec{\Omega}_o|}{G \Sigma_{\text{gas}}} \geq q , \quad (2)$$

where C_s is the gas sound speed, $|\vec{\Omega}_o|$ is the norm of the angular frequency vector, G is the gravitational constant, Σ_{gas} is the gas surface density and q is a number of the order of unity. Otherwise, if $|\vec{Q}_o| < q$, a stream will be unstable.

It is important to point out a subtlety: the concept of angular frequency depends on the origin of the coordinate system chosen to describe the motion, and contrary to the case of the rotating sheet, there is not an obvious single choice for all streams in a galaxy merger. We will come back to this point in section 4, when we compare the results of this section with numerical simulations, for validating how well Eq 1 describes the motion of individual streams and therefore if the stability criteria given by Eq 2 is valid or not. We will also compute in section 4, a value for q that predicts better the stability of streams in the merger.

In the case that all the streams are coplanar and orbit around the same point, we recover the standard Toomre Q parameter for a rotating sheet ($= C_s \Omega / G \Sigma_{\text{gas}}$; Toomre 1964), since now the direction of $\vec{\Omega}_o$ and the origin O chosen to describe the motion, is also the same for all streams.

3. Simulations of gravitational fragmentation in galaxy mergers

In the following we perform a set of simple numerical experiments aimed to test the stability parameter (Eq. 2) and to study the minimum resolution required to have fragmenting clumps. These experiments are constructed as simple as possible, in order to guarantee that the gas fragmentation is only due to gravitational instability.

The simulation consists on the merger of two equal mass disk galaxies and we let the two galaxies collide in a parabolic orbit with pericentric distance $R_{\min}=7.35$ kpc. The simulations start with an initial separation of 49 kpc, where the separation distance is measured between the mass centers of the two galaxies and the initial inclination angle between disk planes of individual galaxies is 90° . The galaxies are initialized using the code GalactICS, in particular we used their ‘Milky Way model A’ (see Kuijken & Dubinski 1995 for details). In each galaxy model, we include a gaseous disk with the same exponential profile as the stellar component (Kuijken & Dubinski 1995) and with a total gas mass corresponding to the 10% of the total stellar disk mass. The gas has an isothermal equation of state, $P = c_s^2 \rho$, where the sound speed is fixed at $c_s = 12.8 \text{ kms}^{-1}$, corresponding to a gas temperature of $\sim 2 \times 10^4 \text{ K}$. In our simulations, we use the following internal units : $[\text{Mass}] = 5.8 \times 10^{11} M_\odot$, $[\text{Distance}] = 1.2$ kpc and $G=1$. The total number of particles is 420,000, being 200,000 for sampling the gas, 120,000 for the dark matter halo, 80,000 for the disk component and 20,000 for the bulge.

The simulations were evolved using the SPH code Gadget-2 (Springel 2005), up to a time $t=160$ (in internal time units), which correspond to a point where the galaxies are after their third (and final) pericentric passage and in which most of the gas ($> 80\%$) has been fueled to the central kpc. Fig 1 (a, b, c, d) show the evolution of the system at four times $t = 32$ (a), 54 (b), 120 (c) and 136 (d) which corresponds to before (a) and after (b) the first pericentric passage, second pericentric passage (c) and in their third pericentric encounter (d).

3.1. Resolution Requirements

Before analyzing the stability of gaseous streams it is necessary to check that we have the (gravitational) resolution required to resolve the fragmentation of streams into collapsing clumps, for that reason we performed a convergency test. We restarted the original simulation with a gravitational softening length $\epsilon_{\text{soft}}=0.4$ at $t=132$, with the following gravitational softening ϵ_{soft} : 0.04, 0.02, 0.01, 0.008, 0.006 in internal units.

Fig 1 (e, f, g, h) shows the evolution of the restarted simulation at a later time $t=134$, in a region of radius 2 internal distance units (2.4 kpc) for different gravitational softening

lengths: 0.4(e), 0.04(f), 0.01(g), 0.006(h). Fig 1 (e, f, g, h) shows that as the softening lengths decrease, we find more gas fragmentation until a point in which the resulting simulations converge. We find convergency of the results for $\epsilon_{\text{soft}} \leq 0.01$ and for that reason, we choose to use in the following section a gravitational softening length of $\epsilon_{\text{soft}} = 0.01$.

The convergency can be understood if we take into account that over 99.6% of the particles in such region fulfill the condition $\lambda_{\text{rot}} \geq 4\epsilon_{\text{soft}}$ for $\epsilon_{\text{soft}} = 0.01$ and below. The convergency when λ_{rot} is resolved for all particles, is the first suggestion for supporting our definition for λ_{rot} in this environment with disordered motion ($\lambda_{\text{rot}} \equiv \pi^2 G \Sigma_{\text{gas}} / |\vec{\Omega}_o|^2$). Because the evidence that the minimum requirement to resolve fragmentation at least on the largest scales, is to be able to resolve gravity below our definition for the largest unstable scale λ_{rot} , supports the approach of using results from standard stability analysis in §2.

4. Test of the stability criteria $|\vec{Q}_o|$

After checking the resolution needed to resolve fragmentation at least on scales below those of the largest collapsing clumps, we will focus on testing the stability criteria discussed in §2 (Eq. 2). Since most of the streams in the inner 2.4 kpc of the system already fragments for $T \sim 2 \times 10^4 \text{K}$, we will perform a set of simulations in which we increase the temperature and see how some streams become stable. We will check if the criteria given by Eq 2, successfully predicts if a stream should be stable or not.

Fig 2 (a, b, c, d) shows the evolution of the gas density for the system restarted with a gravitational softening length of $\epsilon_{\text{soft}} = 0.01$, at $t=132$, for different temperatures $T=2 \times 10^4$ (a), 2×10^5 (b), 5×10^5 (c) and 10^6K (d) and evolved to a later time $t=133.2$. The comparison between different temperatures (a to d in Fig 2) clearly shows that more streams become stable as we increase the temperature.

Fig 2 (e, f, g, h) shows $|\vec{Q}_o|/q$ computed for each particle at the time in which all the simulations were restarted with $\epsilon_{\text{soft}} = 0.01$ ($t=132$), for different temperature $T=2 \times 10^4$ (e), 2×10^5 (f), 5×10^5 (g) and 10^6K (h). For computing $\vec{\Omega}_o$, we choose for simplicity one point as origin O of the coordinate system for all streams. Our choice is the total center of mass (G) of the merging galaxies, because the system as a whole orbits around G and is also an inertial point for an isolated merger (in absence of external forces). From Eq. 2, the threshold for stability should be around $|\vec{Q}_o|/q = 1$, which corresponds to the yellow particles in the figure 2, the green and blue particles should be unstable and the red ones stable.

The direct comparison of both sides of Fig 2 (a-e, b-f, c-g and d-h pairs), shows overall

a good agreement between the predicted unstable streams (showed in green and blue in Fig 2 (e, f, g, h)) and the streams that eventually fragments on the corresponding Fig 2 (a, b, c, d). In particular, the bluest stream in Fig 2 e (and in light green in Fig 2 h) is the most unstable region and the only one that strongly fragments in all simulations (including Fig 2 d) besides the increase in temperature up to 10^6 K. For the comparison of both sides of Fig 2 is important to perform a counter clock-wise rotation of Fig 2 (e, f, g, h) in about 20° , to take in account the orbital motion of the system between $t=132$ (e, f, g, h) and $t=133.2$ (a, b, c, d).

We find that the stability of gaseous streams is better described for a threshold value $q \sim 0.4$, in fact, we plot $|\vec{Q}_o|/0.4$ in Fig 2 (e, f, g, h). This is approximately a factor of 2 lower than the value expected for an uniformly rotating isothermal disk ($q = 1.06$; Goldreich & Lynden-Bell 1965). However, it is important to emphasize that the actual value of q should depend on the origin O chosen for the coordinates system.

5. Summary

In this Letter, we have studied the gravitational stability of gaseous streams in the complex environment of a galaxy merger, using hydrodynamical simulations.

We find that the standard Toomre Q stability parameter can be generalized for case of gaseous streams orbiting around the merger remnant, by using the angular frequency vector of each stream. This is valid as long as the orbital motion of a stream can be well approximated by the rotational motion around the local center of gravity on a given plane, which is what happens in the inner regions of the merger remnant.

We test our generalized stability criteria, $|\vec{Q}_o| \geq q$, using SPH numerical simulations specially designed for that purpose. We find that this criteria successfully predicts the streams that will be gravitationally unstable to fragment into clumps. We find that the stability of streams is better described choosing a threshold value $q \sim 0.4$.

The generalization of λ_{rot} in a galaxy merger, is also relevant for the formation of massive globular-type clusters since its associated mass $M_{\text{rot}} = \Sigma_{\text{gas}} (\lambda_{\text{rot}}/2)^2$, is related to the characteristic mass of the most massive clusters that are able to form (Escala & Larson 2008; Shapiro et al. 2010) and has a role in the triggering of star formation, since it correlates with the galactic star formation rate (Escala 2011).

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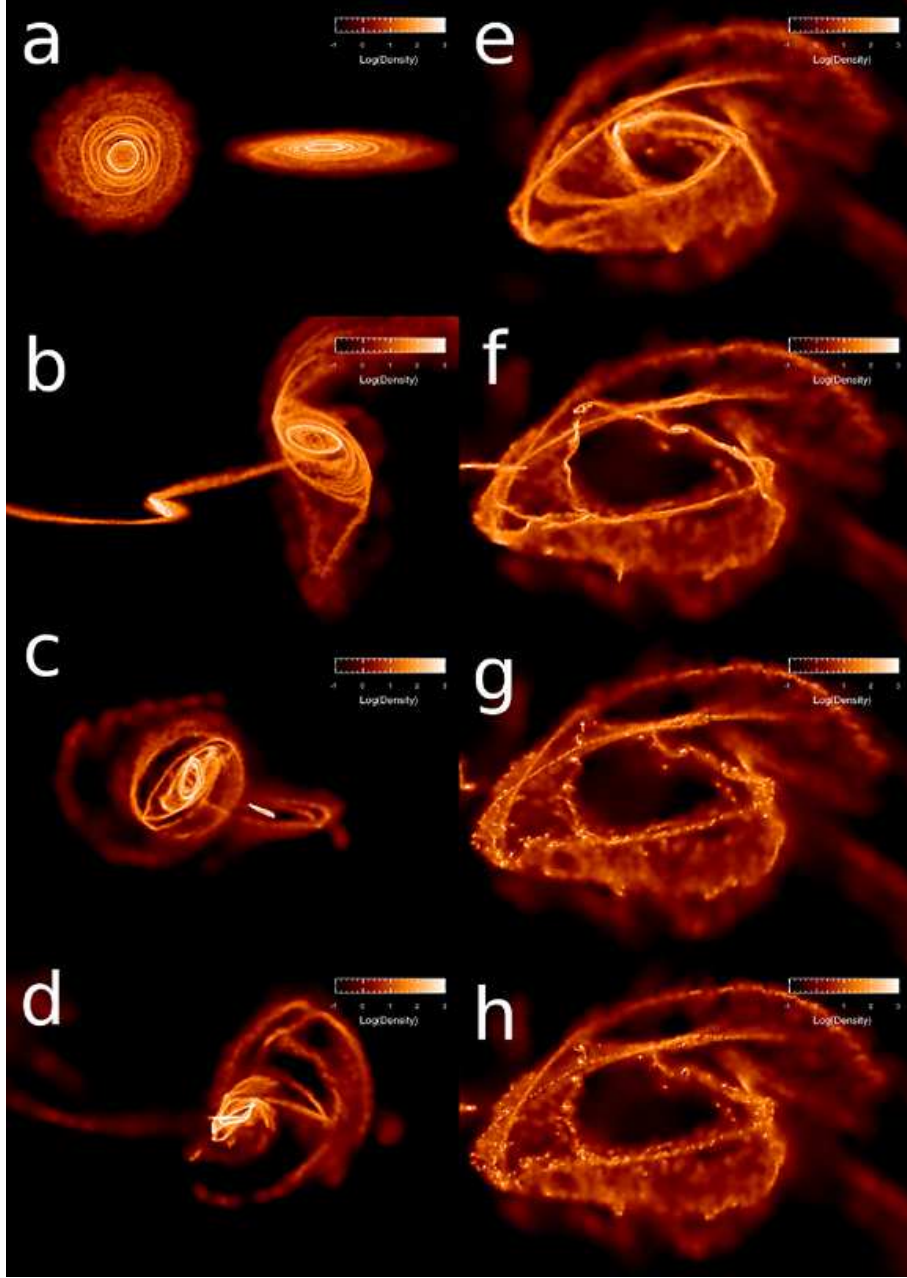


Fig. 1.— Gas density distribution during the evolution of the galaxy merger showed in a logarithmic scale. Left side panels in the figure show the density distribution in a box of side 25, in internal units, at the following times $t = 32$ (a), 54 (b), 120 (c) and 136 (d). Right side panels show a zoom in of the simulation restarted at $t=132$ (box of side 4 in internal distance units), evolved up to time $t=134$ using the following gravitational softening lengths: 0.4(e), 0.04(f), 0.01(g), 0.006(h).

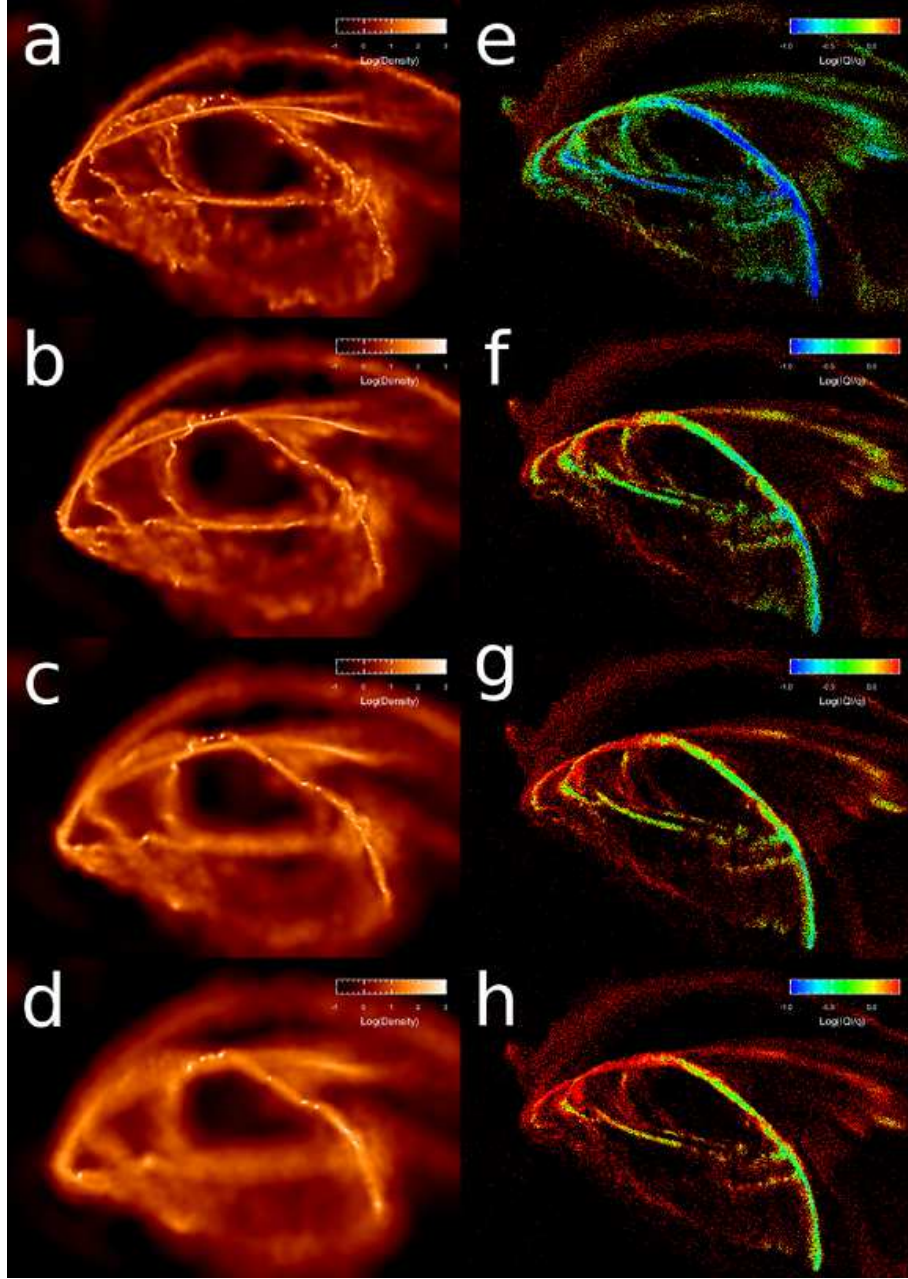


Fig. 2.— Left side panels show the evolution of the gas density distribution at $t=133.2$, for different temperatures $T=2 \times 10^4$ (a), 2×10^5 (b), 5×10^5 (c) and 10^6 K (d). Right side panels show the predicted $|\vec{Q}_o|/q$ for each particle, which is computed at the restarting time $t=132$, for the following temperatures $T=2 \times 10^4$ (e), 2×10^5 (f), 5×10^5 (g) and 10^6 K (h). In all figures, the boxes have a side of 4 internal distance units.